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Wavepackets in boundary layers close to transonic speeds

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Abstract

In practical situations, natural transition determines the transition to turbulence process. Experimental evidence suggest that the wave packet evolution is related closely to natural transition. The major part of numerical works on wave packets are focused on incompressible, supersonic and hypersonoc flows, subsonic ones are probably the less researched. A compressible DNS code was developed, several code validation tests were performed, including a simulation of an experiment of wave packets [1]. The evolution of wave packets on compressible boundary layer in a flat plate is studied by Direct Numerical Simulations (DNS), to investigate the effect of Mach number in the initial nonlinear stages. For Mach 0.9 were considered three cases: linear, nonlinear and interaction between two packets. Results suggest that subharmonic mechanism is the most probable scenario at the initial nonlinear stages.

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Keywords: Compressible boundary layer, subsonic boundary layer, natural transition, wave packet, DNS simulation.

1. Introduction

Transition in boundary layers is still an open field of research. Substantial progress was made in the nonlinear regime of monochromatic Tollmien-Schlichting (TS) waves, but transition in practical situations involves modulated TS waves. Wave packets were found to be good models for transition occurring in real situations and have received some attention, in particular for the incompressible regime [2,3,1,4,5]. Since airplanes always fly in the compressible regime it is important to investigate the effect of Mach number, which is a lot less researched, in particular close to sonic speeds. As the Mach number increases, oblique waves become progressively more unstable relative to two dimensional waves and the spanwise spectrum of the packet broadens. Above Mach=0.7 oblique waves become more unstable than two dimensional ones. These aspects may enhance different types of mode interaction and affect the packet behavior.

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2. Methodology

The problem was studied via Direct Numerical Simulations. The code was developed in a nonconservative formulation, using the velocity components, the density and the internal energy as the directly time integrated variables. The fluid was considered an ideal gas. The equations were discretized by compact finite-differences in all directions. A three diagonal computational stencil that provided 4^{th}-order spectral-like accuracy was developed for the code, following[6]. For the time integration is used a 4^{th} order Runge Kutta scheme. Grid stretching was implemented for the wall normal direction. To control spurious oscillations a 10^{th} order filter was applied. The code was parallelized using the so called slab (1D) and pencil (2D) decomposition which is particularly suitable for compact schemes, parallelization was implemented using the library[7]. Code was successfully tested by comparison with results of comprehensively documented flows, such as the lid-driven cavity flow, subsonic boundary layer profiles, calculations of linear stability theory (LTS) and the simulation of an experiment on wave packets[1].

The boundary layer studied is initiated from an uniform incoming flow that reached the leading edge of a flat plate. The boundary conditions at the inflow were uniform Dirichlet for velocity and temperature, while the pressure was extrapolated from the internal grid points assuming a zero first derivative in the streamwise direction. For the outflow, the pressure was fixed, while velocity and temperature were extrapolated. At the outerflow pressure was fixed and a homogeneous Neuman condition was applied for the other variables. At the wall, Dirichlet conditions were imposed for velocity and temperature, and for pressure a compatibility condition was used[8]. At the outflow a buffer zone was implemented via streamwise grid stretching to prevent non-physical wave reflections. The spatial component of the disturbances were introduced by a localized suction and blowing circular region on the plate and the temporal component is contructed by the superposition of 80 Fourier modes. To reduce the computational cost, the domain is reshaped in the streamwise and spanwise directions, as shown in figure 1. It is done several times during the simulation, to discard the part of the domain where the packet already past in upstream direction and to increase the domain in the spanwise direction to take into account the packet spread.

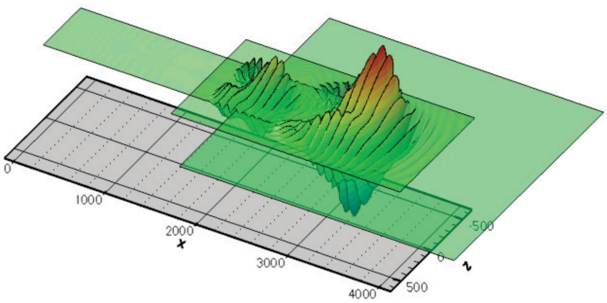


Fig. 1: The computational domian is reshaped during the simulation to reduce the computation time.

3. Results

The reference length used for nondimensionalization of the parameters was the displacement thickness $\delta^*(x)$ at the excitation location. The velocity scale was the free-stream velocity.

Prior to simulations of wave packets at subsonic Mach numbers, results of periodic wave excitation were successfully compared with the linear stability theory. To validate the code for wave packets problems it was simulated the experiment reported on[1] for incompressible boundary layer. The nondimensional parameters were: the displacement thickness Reynolds number at the excitation 835, Mach 0.2 and Prandtl number 0.7. The disturbance used to excite the packet was built from a flat spectrum of Fourier modes covering a range of frequencies substantially wider than the boundary layer unstable frequencies[1]. The effective domain size (excluding the buffer zones) was $2000 \times 20 \times 900$ units in the streamwise, wall-normal and spanwise directions respectively, and the grid had $1001 \times 101 \times 241$ points.

Comparison between data experiment and DNS results at all measurement points are presented in figure 2, at the plane $y = 0.6\delta^*(x)$ which corresponds to the first maximum of the eigenfunction. The higher differences are present at the initial measuring points, downstream the agreement is better.

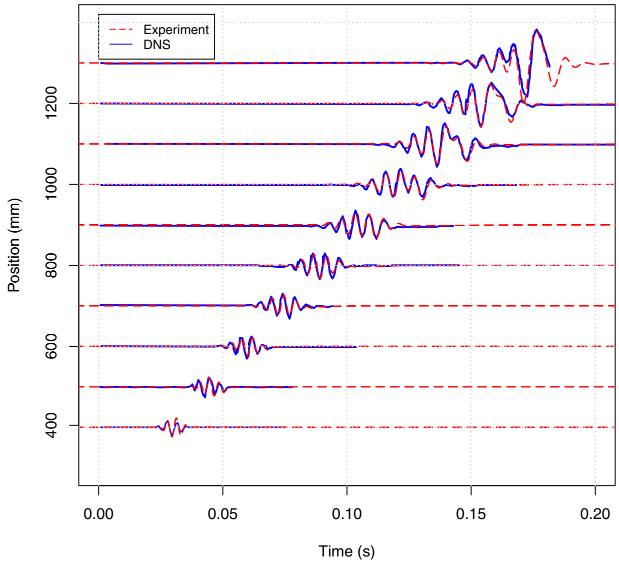
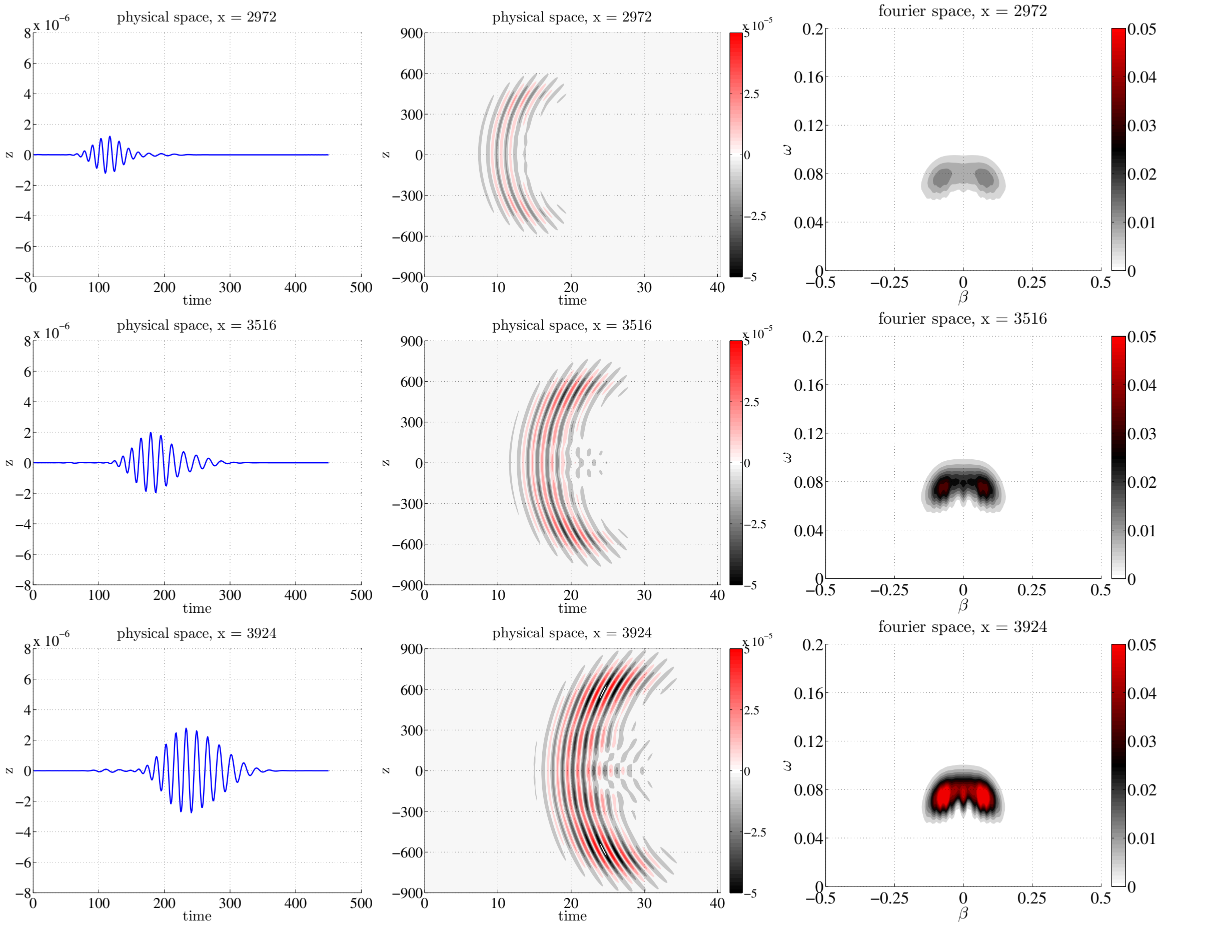


Fig. 2: Comparison between experiment and DNS simulation at the centerline at the plane $y = 0.6\delta^*(x)$

By changing the amplitude of the packet were considered three cases at Mach number 0.9: linear, nonlinear and interaction between two packets. The values of the others flow parameters were the same as in the incompressible case. The packet evolution was studied along spanwise direction and time, at several streamwise fixed points, as was done in the experiment.

3.1. Linear wave packet

In figure 3 is shown the behavior of linear packet at Mach 0.9. Results for several similar amplitudes at perturbation point were tested to guarantee linear behavior by comparison of scaled packets in the same factor of the perturbation amplitudes. As expected from compressible linear stability theory oblique modes are the most amplified modes. The growth rate disturbance in compressible boundary layer is lower than in the incompressible case, for this reason it was necessary a domain two times larger to observe a consistent amplification at the centerline. In these simulation the computational domain was reshaped as described in the methodology.



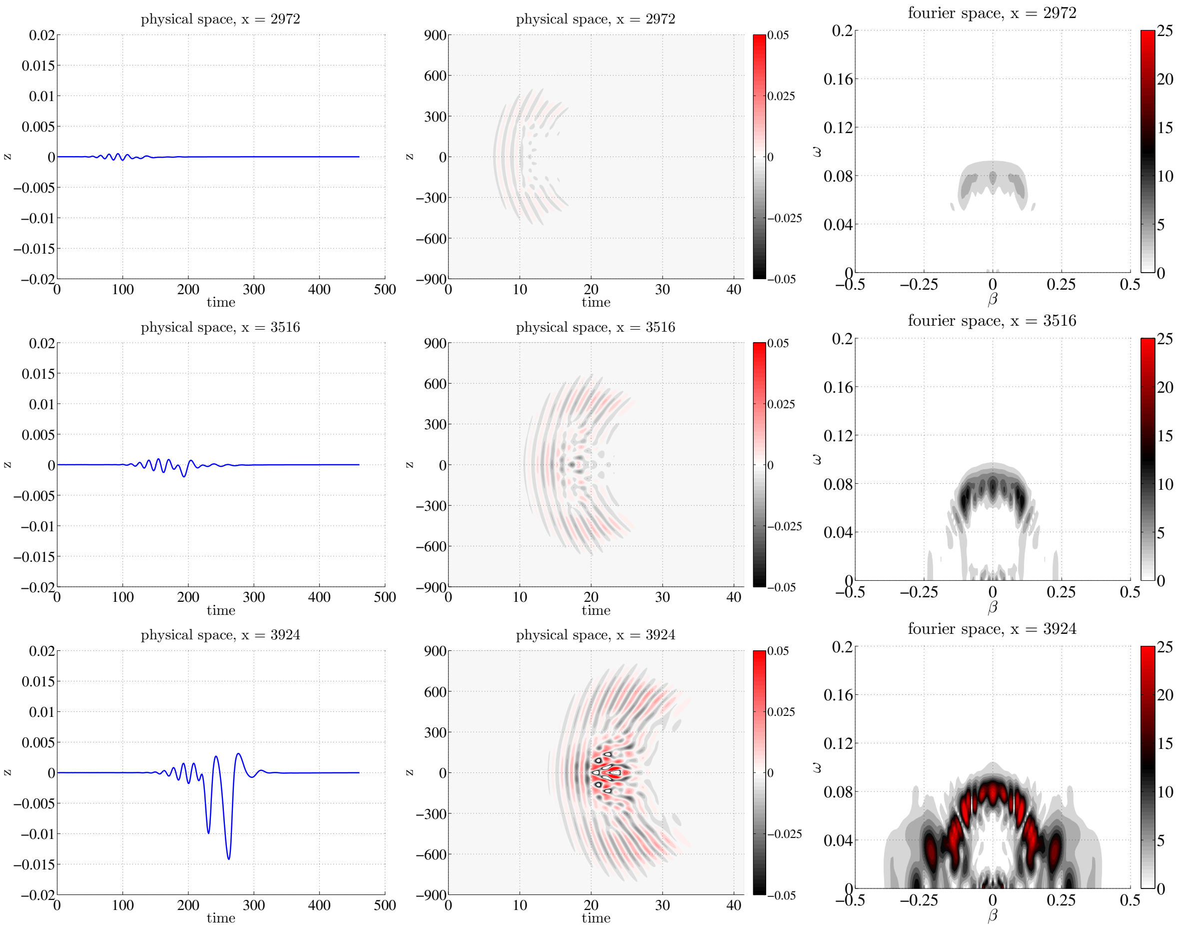
a) Physical space b) Fourier Space

Fig. 3: Linear wave packet evolution in time for Mach number 0.9, at three positions in downstream direction. a) Physical space, b) Fourier space.

3.2. Nonlinear wave packet

Careful attention was given to the excitation magnitude. We wanted to study the nonlinear regime of a packet as it evolves from previous linear regime. A pulse excitation 100 times larger than in the linear case triggered at the source nonlinear behavior strong enough to remain self-sustained and govern the packet evolution. The initial amplitudes (not showed here) are similar to amplitudes used in studies of incompressible wave packets. Again, due to lower growth rates than in the incompressible case the domain considered is larger, in a small region the packet is strongly amplified as is shown in figure 4. In physical space at the last measuring point the wave packet has in the center a structure similar to λ vortices and in the corresponding spectrum can be observed a band of unstable β modes with frequencies that suggest the presence of the subharmonic mechanism. In the physical space can be seen that the energy transported by the packet is concentrated in its center, due to the presence of the larger amplitudes in this region.

In Gaster's studies[9] the incompressible linear packet grows by less than 50% along its centerline evolution which covers a fraction of the Reynolds number range of the current compressible study. In the subsonic regime, as the Mach increases the TS-waves become more stable. Moreover, owing to enhanced three-dimensionality, the dispersive effects are also more relevant. As the packet evolves the modulation effects reduce and eventually the packet amplitude should start to grow in physical space. What was somewhat unexpected was that this would take so much longer than for incompressible flow. The results show that wave packets in the Mach number investigated are much more resilient to nonlinear behaviour than their incompressible counterpart.

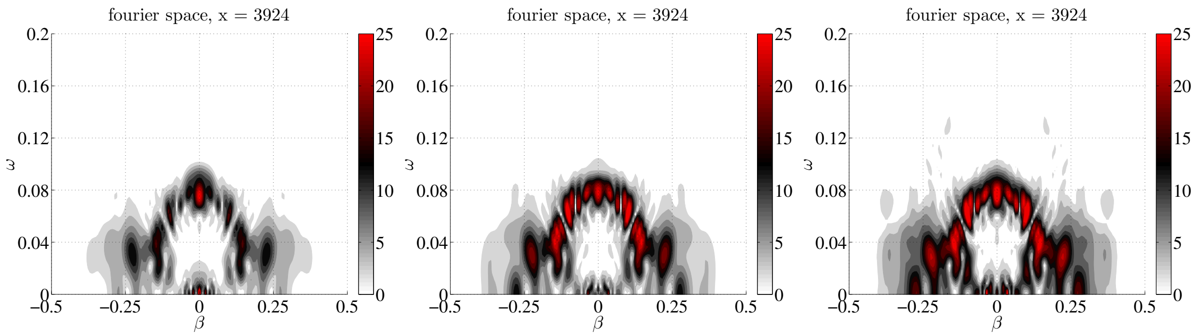


a) Physical space b) Fourier Space

Fig. 4: Nonlinear wave packet evolution in time for Mach number 0.9, at three positions in downstream direction. a) Physical space, b) Fourier space.

3.2.1. Stability criteria

There is no an unique criterion to choose the plane along the plate to measure the velocity component of the wave packet. This choice influences the results of the stability analysis, as is presented in[10]. In figure 5 are shown the spectra at three y-planes, corresponding to the maximum of the eigenfunction of 2D waves (a), the maximum of the oblique waves (b) and the local maximum defined as $max\{u(y)\}$ (c). As expected, local maximum is similar to the $y = 1.1\delta^*(x)$ criterion, because the studied cases considers tridimensional disturbances. Observed nonlinear behaviour depends on this choice, in the three cases considered here for Mach 0.9, the first criterion was used to compare with the incompressible packet.



a) Plane $y = 0.6\delta^*(x)$ b) Plane $y = 1.1\delta^*(x)$ c) Local maximum $max\{u(y)\}$

Fig. 5: Comparison of spectra calculated at several y planes.

3.3. Interaction wave packet

The previous results indicate that, prior to nonlinear activity, the compressible packet is likely to become a lot wider and longer than incompressible ones. Therefore, in a compressible natural environment it will be more difficult for a packet to evolve in complete isolation. Interacting packet may be a probable scenario and this was here investigated. A simulation was performed in which two packets were excited at the same time. The excitation points were one next to the other in the spanwise direction. This distance was chosen arbitrarily. In order to keep a good basis for comparison, an to maintain the energy added to the flow constant, the excitation amplitude of each packet was half that of the isolated packet above discussed. The evolution at the center of one of the packets is initially similar to the isolated one, with half the amplitude. At some stage distortions are seen. They are associated with the packet interaction, but disappear later. Results along the centerline of the domain also do display strong distortions at the centerline. Figure 6(a) and (b) shows the evolution of the interacting packet in physical and $x-z$ and $\alpha\times\beta$ planes. The packets merge some distance downstream, and even at later stages display substantial differences from the isolated case. In the linear regime the spectra displays a pattern that is linked with the symmetry of the interacting packet case. At later stage modes outside the linearly unstable band arise, suggesting nonlinear activity. It is clear that the interacting packets are more prone to nonlinear behavior. Even under interacting conditions the nonlinear activity is relatively weak. The most salient feature is a band of oblique modes that are close to a subharmonic of the dominant modes. of commercial airplanes often occur under adverse pressure. This scenario is also being considered.
The relative positions of the packets determines strongly their evolution, in this case they are one next to the other, so it could be expected that the behavior is similar as one packet, however, figure 6 shows a different evolution when compared with the previous cases, again, oblique modes are dominant. In future works, it is expected that simulating the evolution even further and extending the parameter space will bring more insight into this important, and as yet unknown, scenario.

4. Conclusions

A compressible DNS code was developed and tested for wave packet evolution in a flat plate boundary layer. At Mach 0.9 were considered three cases: linear, nonlinear and interaction between two packets. The Mach number has an stabilizing effect due to lower growth rates predicted by linear stability theory, in the cases considered here, oblique modes were the most amplified in the linear case and in the nonlinear packet frequencies of unstable band of spanwise wave numbers suggest the presence of subharmonic mechanism. Relative positions between packets influences strongly the behaviour, a parametric study is needed to get an insight in this kind of problem.

Acknowledgements

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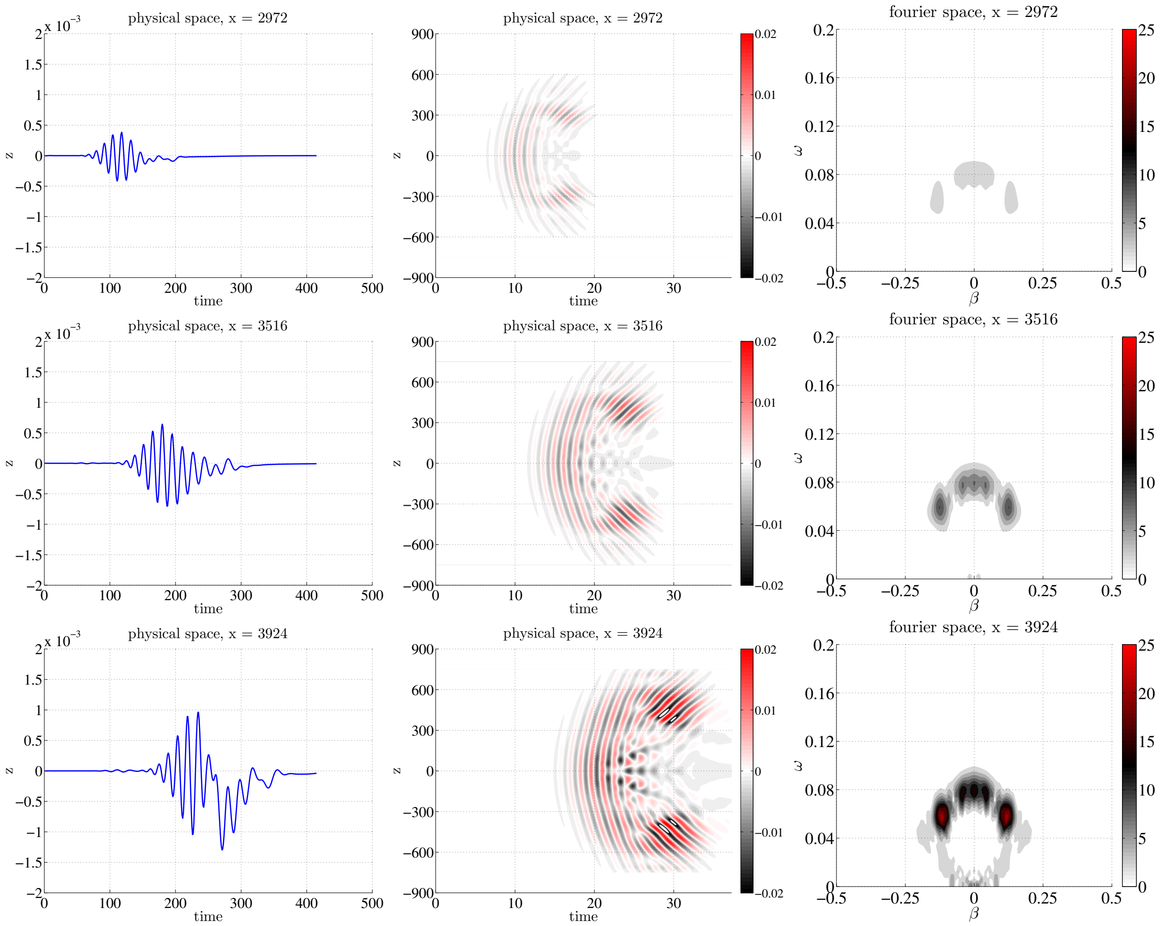

a) Physical space

b) Fourier Space

Fig. 6: Interaction between two packets for Mach number 0.9, at three positions in downstream direction. a) Physical space, b) Fourier space.

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